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Ultrasonics Sonochemistry 11 (2004) 119–123
Ultrasonics SONOCHEMISTRY
www.elsevier.com/locate/ultsonch

High-speed observation of acoustic cavitation erosion in multibubble systems

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Abstract

Cleaning and erosion of objects by ultrasound in liquids are caused by the action of acoustic cavitation bubbles. Experiments have been performed with respect to the erosive effect of multibubble structures on painted glass surfaces and on aluminium foils in an ultrasonic standing wave field at 40 kHz. High-speed imaging techniques have been employed to investigate the mechanisms at work, in particular bubble interaction and cluster formation near and at the object surfaces. It was found that different prototype bubble structures can contribute to the erosion process. Some are bound to the surface, which seems to act as a bubble source in this case, while others also exist independently from the object. Cleaning and erosion effects at the pressure antinodes can vary strongly as they depend on the emerging bubble structures. These, in turn, seem to be substantially influenced by properties and the history of the surface.

PACS: 47.55.Bx; 43.25.Yw
Keywords: Cavitation erosion; Ultrasonic cleaning; High-speed imaging; Bubble structures

1. Introduction

It is well known that cleaning and erosion take place at objects exposed to ultrasonic fields in liquids [1–4], and it is the common notion that both effects are caused by the same underlying phenomenon: the strong collapse of acoustic cavitation bubbles which is accompanied with high local pressures. While the damage from single bubble collapse events near boundaries has recently been studied experimentally in great detail, e.g. via bubbles created by focused laser light [5,6], the erosive action of many and longer living bubbles and bubble structures [7,8], as they occur in applications, still needs better documentation. Here we present results of high-speed imaging of cleaning and erosion processes performed in a 40 kHz ultrasonic reactor, see Fig. 1. The motivation was to confirm that the bubbles are the main agents of the indicated effects. Furthermore, it was intended to highlight the role of spatial bubble distributions and structures. It was found that the detailed appearance of the bubbles can be differentiated into several prototype structures. Some images are shown and discussed in the following sections. A deeper understanding of the underlying mechanisms might promote approaches to better control the cavitation action.

2. Cleaning activity

Most experiments have been performed at a constant acoustic power of the ultrasonic bath of 142 W (intensity at the emitting surface 0.43 W/cm^2). Up to the maximum acoustic power (712 W corresponding to 2.15 W/cm^2), which could only be operated for short time, the observed effects and bubble structures did not change qualitatively, which means that the given results are representative for the device used.

Fig. 2 presents one frame of a high-speed recording taken at 2250 frames per second with a HiSIS 2002 CCD camera. The viewpoint is from the side, and bubbles appear bright as they scatter off the light from a continuous illumination (for similar high-speed recording methods see [9,10]). The images document the cleaning of a painted glass surface near the center of the ultrasonic bath. The ink of a waterproof marker pen (edding

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doi:10.1016/j.ultsonch.2004.01.006

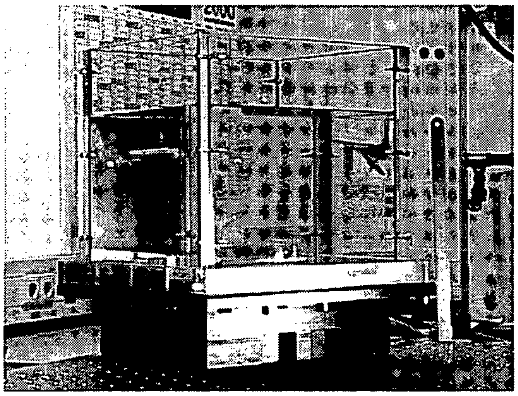

Fig. 1. Ultrasound device equipped with transparent walls and eight piezoceramic transducers at the bottom (L3-Communications ELAC Nautik) operated at 40 kHz and 142–712 W acoustic power (200–1000 W electrical power). The intensity at the radiating bottom plate corresponds to 0.43–2.15 W/cm^2. The liquid is tap water with a free interface to air on the top, volume 16.4(w)$\times$20.2(l)$\times$14.0(h) cm^3.

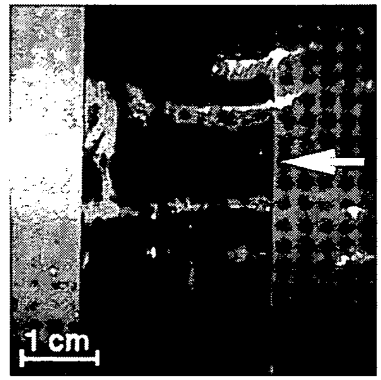

Fig. 2. Thin glass plate exposed to the cavitation field of the resonator. One surface was painted with black waterproof marker. The characteristic horizontal cleaned areas are located in the same planes as the double layer jellyfish bubble structures, and on the top right such a structure is just active (bubbles appear in white, ink in black, cleaned areas in light grey as the background).

3000) has been applied evenly on one side of a microscope slide. Double layer structures of bubbles are acting on the glass surface. These "jellyfish" streamers (also present without an object) appear in standing waves between nodal and antinodal pressure zones [11] which develop in the rectangular resonator roughly as planes parallel to the water surface. The glass plate has been placed vertically into the bath and thus is directed perpendicular to the standing wave planes. [1] Pressure antinode regions are avoided by the bubbles in this case, apparently because of inverted primary Bjerknes forces [12,13]. Indeed, the erosive or cleaning action is concentrated in horizontal stripes that correspond to the bubble layer positions. The ink in the antinodal plane (indicated by the arrow in Fig. 2) is not removed in the right part of the plate.

A close-up of an eroding jellyfish structure is shown in Fig. 3. Here, the view-point is onto the edge of the glass plate, and bubbles appear dark with a brighter background. The bubbles are concentrated mainly in the two horizontal layers indicated by the dashed boxes. Between the layers a nodal plane of the pressure is located. A spherical bubble cluster is moving from a zone of higher pressure towards the upper bubble layer and merges with the bubble cloud. Dark material (not to be confused with bubbles) is emitted from the left side of the plate into the liquid because of the erosion process. The liquid on the right side stays transparent as only the left side was painted.

Fig. 4 shows the initial process of bubble structure formation at power-on of the sound field. Already existing bubbles on the surface (white spots in the first frame) grow, translate and cluster. Shortly later, structures form (third frame, dashed box) where bubble streams seem to originate from a small point region on the surface and end in a bubble cloud. We termed such structures "smoker" because of the similarity to smoke clouds from a fire. The point-like smoker tip has a strong erosive power. The arrow in the fourth frame marks a small streak just cleaned from ink by the upwards moving smoker tip. Still later, jellyfish layers appear (last frame, dashed box) and can start to erase ink in horizontal stripes (compare Fig. 2 which was taken from a different recording sequence).

Larger clusters or clouds that form the ending of a smoker can as well exist alone on the surface, without a visible connection to a point-like source. In Fig. 5, which shows some frames from the same recording as Fig. 4, the main erosion takes place by such more or less circular clouds of a few millimeter diameter. Their preferred direction of motion is rather vertical than horizontal, i.e. perpendicular to the standing wave planes (the vertical cleaned area at the left side of the plate in Fig. 2 is due to such structures, too).

The sequence of four frames in Fig. 5 covers a time of 2000 ms, and it can clearly be seen that a cluster on the right enlarges a clean area (dashed rectangle given for reference). From this recording, one can estimate the cleaned area as approximately 12.5 mm^2 and therefore an "area cleaning speed" σ of the cluster as 6.25 mm^2/s. In general, of course, this value will depend strongly on the type of surface, contamination, and many other parameters. To get an estimate of the necessary time τ

[1] Strictly speaking, only the pressure nodal zones correspond to planes. Theoretically, the antinodes should be isolated points for a particular mode of the resonator. However, hydrophone measurements (Bruel & Kjaer 8103) revealed that the variation of the pressure amplitude from antinode to antinode within a horizontal plane was only weak, i.e. the vertical nodal planes seem to be less well developed in the resonator used (reasons might be contributions of travelling waves and/or mode fluctuations). Therefore it is justified from a practical point of view to speak of horizontal "antinodal planes".

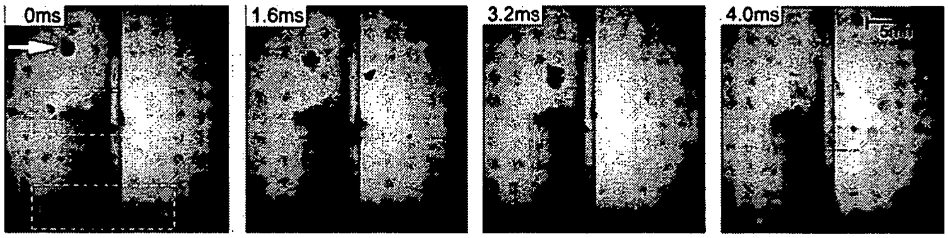

Fig. 3. View onto the edge of the glass plate, timing given in the upper left corners. A double layer (jellyfish) structure is acting on the glass (both layers indicated by a dashed box in the first frame), and a free bubble cluster (arrow) is moving towards the plate and collides finally. Only the left surface is painted, and a black haze of eroded ink is coming off at that side.

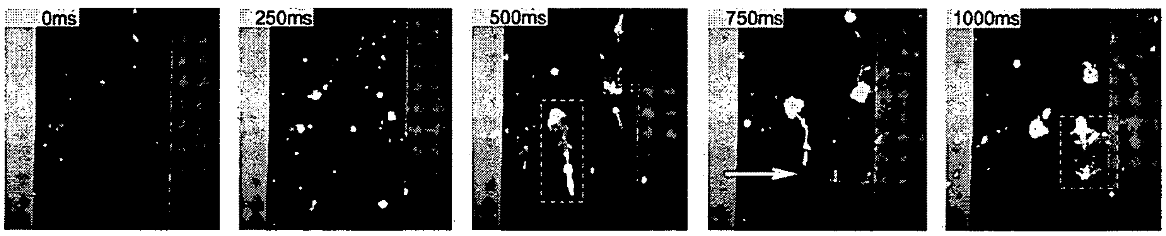

Fig. 4. Formation of cavitation structures on a painted glass plate after turning on the sound field (at $t = 0$ ms). The timing is given in the upper left corners of the frames, scale and colors as in Fig. 2. For details, see text.

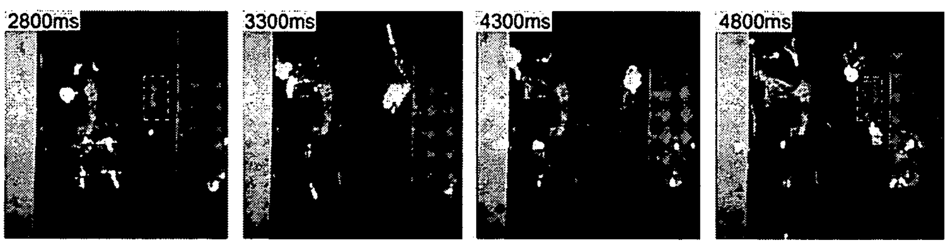

Fig. 5. Frames from the same recording as Figs. 4, but at a later time (given in the upper left corner). Here, the main cleaning process results rather from larger bubble clusters than from jellyfish layers as in Fig. 2. The cleaning pattern seems to show a preference for vertical stripes. The dashed box marks a cleaned zone clearly growing in time (see text).

for cleaning the full object with the indicated bubble structure, one could define an average "structure number density" $n = $(number of clusters)/(surface area) to find $\tau \approx 1/(\sigma n)$. For the example of Fig. 5, we see in average two larger clusters on the visible part of the plate ($\approx$1000 mm^2), which results in a total cleaning time of the order of 80 s. A more elaborate estimation would consider a random walk of the clusters, enlarging this time somehow. In fact, however, at some regions the ink was not erased at all, even after many minutes in the bath. This is a well known feature (and problem) of ultrasonic cleaning applications: The inhomogeneous distribution and action of the bubbles is not a purely random process. The probability for finding a specific bubble structure at a certain surface location is a rather unevenly distributed function. For example, as has been shown before, the jellyfish structure systematically avoids pressure nodal and antinodal zones. For positions and motions of smokers and large clusters, we cannot give a clear picture yet, but it seems that already eroded zones are preferred locations (which means a certain self-amplification of erosion). On the other hand, it is obvious that in any case the pressure nodal regions are places of low activity. This will be confirmed in the next section.

3. Aluminium foil erosion

Missing bubble activity near the pressure node, but as well near the antinode regions could also be demonstrated by aluminium foil erosion recordings. The foil has been clamped into a metal frame and placed perpendicular to the pressure node and antinode planes, as the glass plate in the previous experiments. Recordings took place again from the side in scattered continuous light.

If the foil was placed into the running ultrasonic bath where jellyfish structures had already been formed, the damage corresponded to the bubble layers, see Fig. 6.

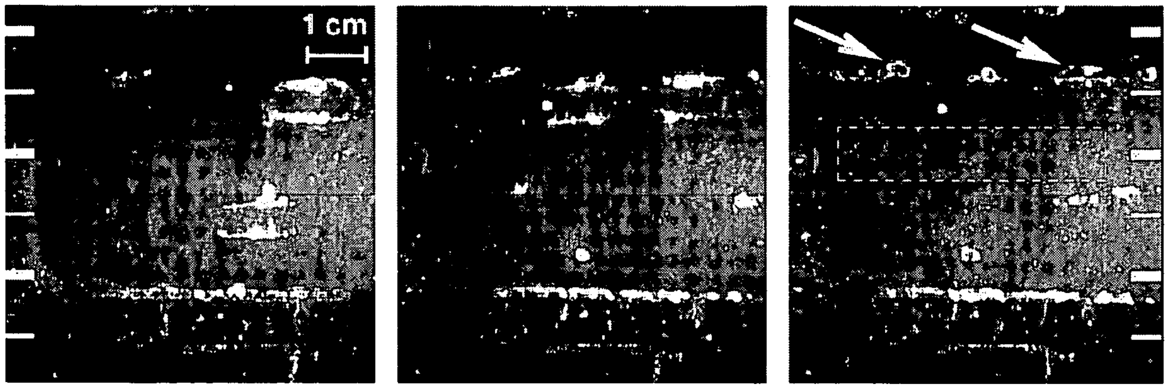

Fig. 6. Three frames from a high-speed recording of cavitation erosion of an aluminium foil in the 40 kHz ultrasound resonator. The device was already running and jellyfish structures were present when the foil was introduced. See text for explanations.

The white thick and thin bars to the left and right of the picture mark the vertical positions of the antinodes and the nodal planes, respectively. The jellyfish layers are just between these planes, and erosion (i.e., holes in the foil, see arrows in last frame) appear exactly there. Between the bubble layers, near the pressure node and antinode regions, no or only limited erosion is observed. In the last frame of Fig. 6, a particular high pressure amplitude region is marked by the dashed box to highlight the remarkable fact that hardly any erosion appeared there (note that the broad horizontal stripe of erosion in the lower part of the picture is an artefact caused by the influence of the clamping frame and is only by chance near to the lower antinode).

If, however, the ultrasound was switched on after immersion of the foil, the bubble structures and the erosion picture was different, see Figs. 7 and 8. Again, the thin and thick white lines to the left and right indicate the position of pressure node and antinode regions. First, single bubbles or small clusters appear on the surface mainly near the planes of maximum sound pressure (one antinodal region is marked by the dashed box in the first frame of Fig. 7). Within about a second, the small clusters partly move and merge into larger ones. Some initial bubbles develop into a smoker structure. In Fig. 7, two of them are indicated by arrows that point to their tips. Later, also jellyfish structures

Fig. 8. The cavitation and erosion pattern from the same recording as Fig. 7 after roughly 5 min. The erosion has almost stopped. Planes of minimum pressure amplitude are hardly affected. The width of the remaining aluminium stripes corresponds to the width of the jellyfish structures (one is visible left of the center of the picture).

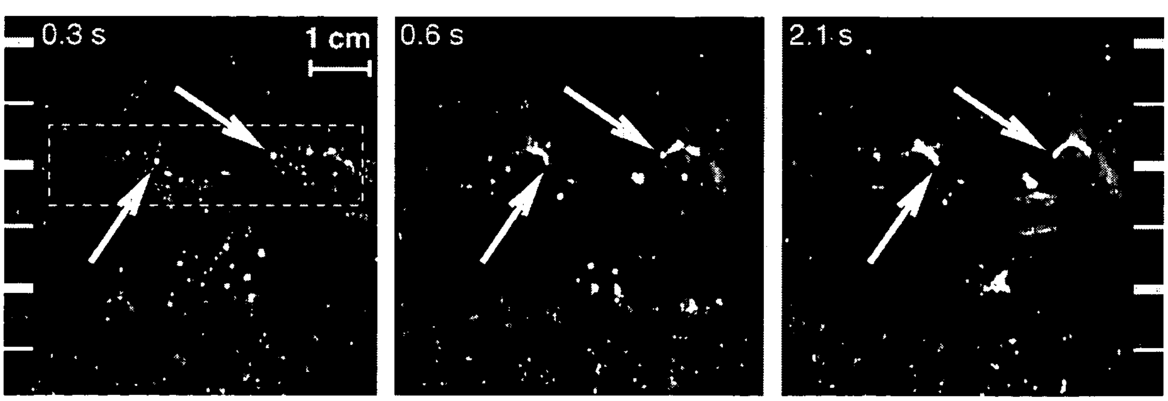

Fig. 7. Similar as Fig. 6, but with the foil introduced before switch on. Small bubble clusters develop to larger ones and to smokers. See text for more details.

appear, but the antinodal regions stay populated by clusters and smokers. The long-term erosion pattern is shown in Fig. 8. The picture now is as expected: pressure antinodes are eroded, pressure nodes stay intact until the end of the experiment.

We conjecture that the spatial distribution of bubble nuclei is a major reason for the observed differences of cavitation and erosion near the antinodes (compare Figs. 6 and 7). If nuclei are located homogeneously in the resonator (after stirring or some time after switch off) the pressure antinodes can be populated by bubbles. If surfaces are present, they probably can sustain a population by acting as bubble sources (for instance by a smoker structure) or by stabilizing a bubble cluster in space. However, if nuclei are distributed unequally in space (e.g., after running the system some time without objects inside, and then introducing the object gently), antinodal regions can be void of bubbles and stay void, i.e. at low or no activity. In particular when only jellyfish structures are present, the antinodes seem to be (and to stay) depleted of nuclei. The reason for this is apparently a repulsive primary Bjerknes force [12,13].

4. Conclusion

We have documented that the cleaning and erosive activity in an ultrasonic bath at 40 kHz is due to cavitation bubbles. In the employed resonator, a well defined horizontal standing wave pattern was formed which had a strong influence on the observed effects (liquid streaming could be assumed to be only of secondary importance). Cleaning and erosion was weak or absent in the pressure nodal regions. The effects near the antinode regions were seen to depend on the particular bubble structure that acted on the surface: Larger clusters and smoker structures, if present, could sustain a high erosive impact there. Jellyfish structures, however, avoided the maximum pressure zones and eroded only between nodal and antinodal planes. The creation of bubble structures attached to the surface (clusters and smokers) did not only depend on the object position in the standing wave, but also on its "history" (immersion before or after power-on). We conjecture that the initial bubble seed distribution (e.g., microbubbles, dust particles, and air sticking to the object) play a significant role for the emergence of these bubble structures. The erosion due to surface attached structures therefore has a certain randomness, while the action by freely existing structures (jellyfish layers) is highly reproducible and apparently more independent of surface peculiarities.

The idea to somehow control the spatial location of eroding bubble structures is, of course, obvious and intriguing. One might think of a pretreatment of objects to foster (or avoid) surface bound bubble seeds. With respect to spatial shift of bubble aggregates, some influence by the sound field might be possible. However, it remains to give a more complete characterization and explanation of the structures to explore ways to control them. Such investigations might promote both ultrasonic cleaning applications and cavitation erosion protection.

Acknowledgements

This work was supported in part by the European Union (INCO-Copernicus contract No. IC15-CT98-0141), the German Ministry of Research and Technology (BMBF project "Untersuchung von Kavitationsfeldern"), and the Deutsche Forschungsgemeinschaft (DFG Graduiertenkolleg "Strömungsinstabilitäten und Turbulenz").

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